Activity 3 – High Temperature Superconductors and Quantum Materials Research

3 High Temperature Superconductivity: Superconductors above 30 K

BCS theory set a limit on the critical temperature that could be achieved by any superconductor at 30 K. However, in 1986 there came another unexpected discovery, a new ceramic material (LaBaCuO) showed a superconducting transition at 35 K above the theoretical BCS limit. Even more surprising was the fact that this material was in fact an insulator at room temperature. This new type of superconductor was named 'unconventional' as it was not described by the conventional BCS theory and, in fact, there is currently no theory to fully describe unconventional superconductors today.

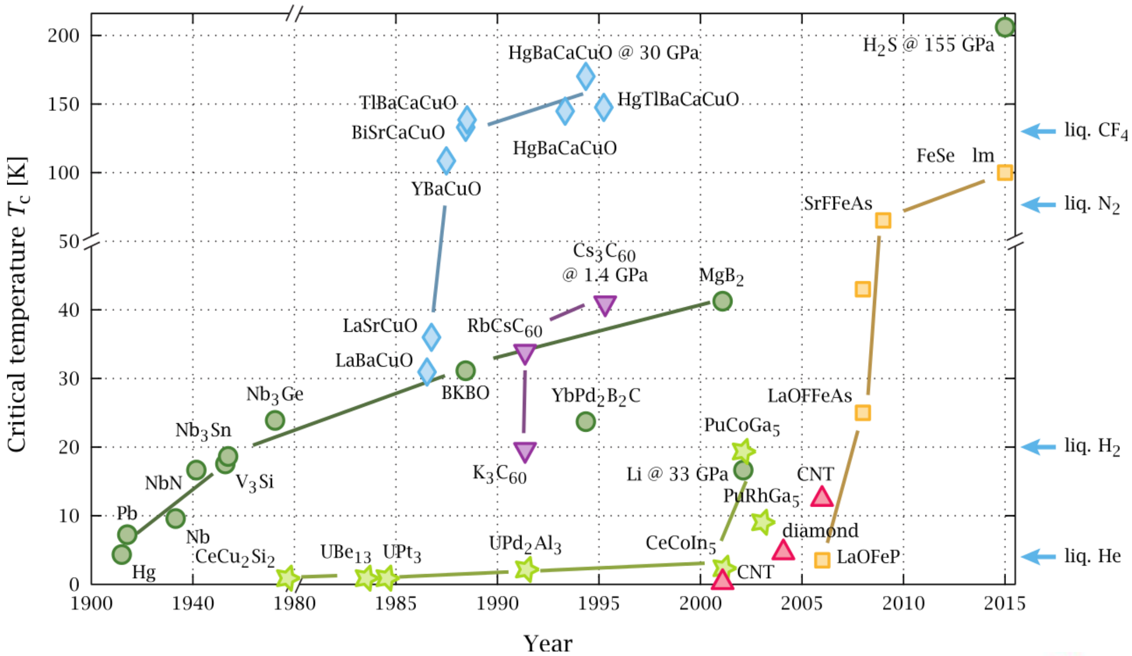

Figure 1: The progression of the critical temperatures of superconducting materi commons license via Wikipedia).

This discovery led to another Nobel Prize in Physics for its discovers Georg Bednorz and Karl Müller in 1987 and launched a whole new research field into high-temperature superconductivity with the goal of achieving room temperature superconductivity. The critical temperatures then rapidly rose throughout the 1980's and it was found that replacing the Lanthanum (La) with Yttrium (Y) gave a critical temperature of 92 K for $YBa_2Cu_3O_{6.5}$ (YBCO). This was a key moment as this was above the boiling point of liquid nitrogen (77 K) which is much cheaper to produce than liquid helium. Figure 1 shows a timeline of the critical temperatures of several superconductors since their

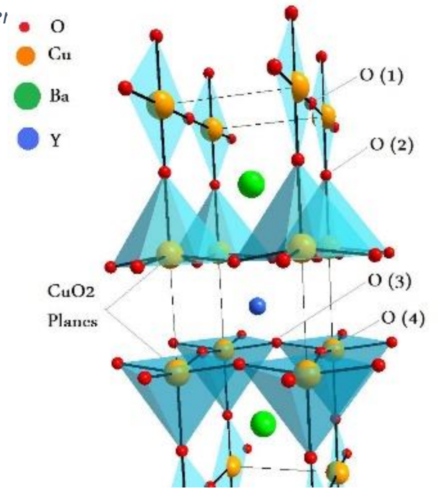

Figure 2: The perovskite-like structure of YBCO. (Obtained under a creative commons license via Wikipedia).

discovery in 1911 to 2015, the current record is 203 K for hydrogen sulphide under extreme pressure[1].

3.2 Structure of Cuprate High Tc Superconductors

LaBaCuO and YBaCuO are known as Cuprate superconductors due to their copper oxide layers and they have a structure that is similar to the common perovskite structure. The superconductivity in these compounds is believed to take place between CuO_2 planes. Figure 2 shows the structure of YBCO whose full chemical formula is $YBa_2Cu_3O_{7-x}$. Varying the value of the 'x' of the oxygen content (O_{7-x}) of $YBa_2Cu_3O_{7-x}$ changes the critical temperature, it is known that the Cu-O planes are crucial for the superconductivity and the T_c is maximised when x = 0.15.

3.3 Particle Accelerators and MRI Machines

Superconducting magnets are made from coils of superconducting wire (conventional superconducting alloys such as niobium-titanium or, more recently, high-temperature superconductors such as YBCO) and can be used to create very large magnetic fields. These fields have allowed the development of nuclear magnetic resonance imaging (MRI) machines in hospitals [Ref 1]. The current in the coils of the superconducting magnets can flow indefinitely with no loss of current detectable via experiment (see **Exercise 2**).

Figure 3: MRI Machine with a large superconducting magnet coil. (Obtained under a creative commons license via Wikipedia).

Superconductors have also been used in Superconducting QUantum Interference Devices (SQUIDs) which are highly sensitive magnetic field sensors that can detect magnetic fields a billion times smaller than the Earth's magnetic field [Ref 2]. These devices were made possible after theoretical insights made by Brian Josephson (Josephson effect) for which he was also

[1] There has recently been a discovery of superconductivity in lanthanum hydride (LaH_{10}) under huge pressures (200 GPa) at 250 K [Ref 4].

awarded the Nobel Prize in Physics in 1973. The large magnetic fields available from superconducting magnets have also allowed CERN's Large Hadron Collider (LHC) in Geneva to achieve the highest energy of colliding particles to date. The LHC consists of a 27-kilometre ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way [Ref 3].

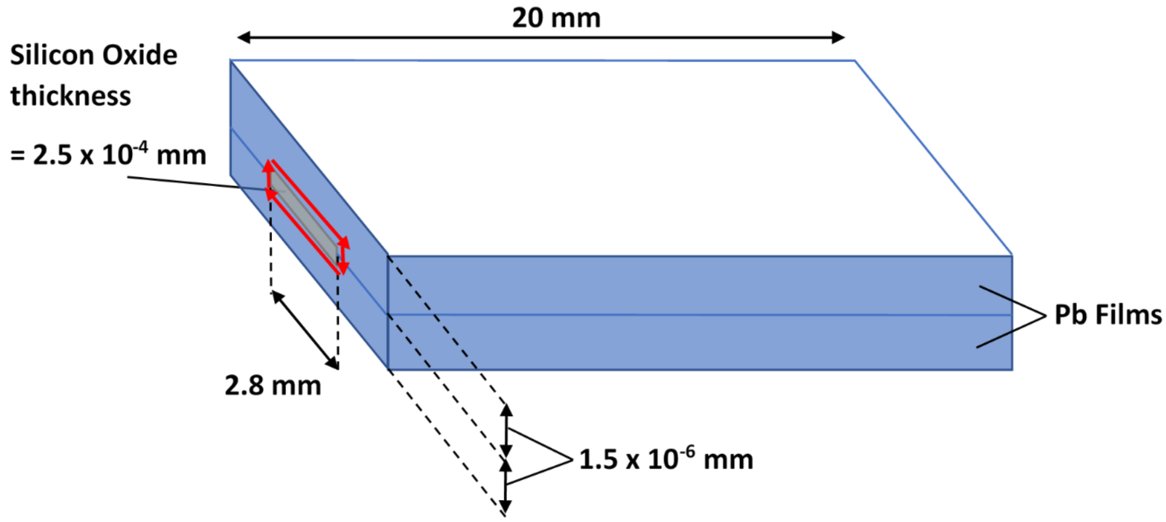

Figure 4: Diagram of Quinn and Ittner's supercurrent experiment using insulating Silicon Oxide and Lead films. The red arrows indicate the path of the current flow.

Exercise 2: In 1962, Quinn and Ittner devised an experiment in which a current was set up around a 'squashed tube', (see Figure 4 above), made from two sheets of lead separated by a thin layer of silicon oxide. Elemental lead is a superconductor below 7.2 K and silicon oxide is an insulator.

The current (I) in an RL circuit (R = resistance, L = inductance) decays exponentially with time (t) such that:

$$I(t) = I_0 e^{\left(-Rt/L\right)} \qquad (2)$$

The tubes' inductance (L) was estimated at 1.5×10^{-13} henrys. After 8 hours, there was no detectable change in the current (to within 1.5% precision i.e. the current was a minimum of 98.5% of its original value).

i. Estimate the maximum possible resistance of the tube for circulating currents. (*Hint: rearrange equation 2 above to find the resistance based on information given about the current*).

ii. How do you think Quinn and Ittner measured the current without disturbing the experiment?

iii. Estimate the maximum possible resistivity $\boldsymbol{\rho_{max}}$ of the lead sheets. Compare your answer with the resistivity of pure lead at 300 K, which is ρ_{300} = 0.2 μΩ.m. (*Hint: remember the formula for resistivity; equation (1) from **Exercise 1***).

3.4 Quantum Materials Research

Since around the mid 2000's the direction of research has shifted away from cuprates and more towards the more general field of quantum materials. A key theme being the idea of emergence, that is, exotic material properties (electronic and magnetic) being the result of the complex interaction of quantum particles, namely strong electronic correlations. Research labs around the world, including here in Cambridge, put these materials under extremes of low temperatures, high magnetic fields and huge pressures in order to coax them into unusual quantum states. A current list of hot topics in quantum materials research includes:

- **Iron-based superconductors**: Discovered in 2006, shows some promise for the next generation of high-temperature superconductors.
- **Topological Semimetals**: New physics lies behind these exciting materials and could lead the way to robust quantum devices.
- **Topological Insulators**: A material that behaves as an insulator but has a surface that can be conducting, with applications for dissipationless transistors for quantum computing.

References

Ref 1

Ref 2

Ref 3

Ref 4

Useful Links

Quantum Materials